THE CAROLINAS COASTAL OCEAN OBSERVING AND PREDICTION SYSTEM (CARO-COOPS)

NOAA Grant No. NA16RP2543

SEMI-ANNUAL PROGRESS REPORT
June 1, 2004 – November 30, 2004

1.0 Introduction

The Carolinas Coastal Ocean Observing and Prediction System (Caro-COOPS) is a NOAA funded program, the two primary partners being the University of South Carolina's Belle W. Baruch Institute (USC) and the North Carolina State University (NCSU). Collaborating institutions include the University of North Carolina at Wilmington (UNCW) and the South Carolina Department of Natural Resources (SC DNR). The program focus is the establishment of the capacity to monitor and model estuarine and coastal ocean conditions in the Carolinas. The goals of the project are to provide real-time predictions and ultimately forecasts to mitigate natural hazards, support management of living resources and marine ecosystems, and facilitate safe and efficient marine operations and support national security efforts.

Caro-COOPS is a wholly integrated system for coastal observations and their application to user-driven research, societal, and economic needs. Thus, Caro-COOPS consists of four related subsystems: (1) the observing instrumentation and platforms, (2) the data communications and management infrastructure, (3) the modeling elements, and (4) the user applications and outreach. The approved Project Year (PY) 03 work plan for the grant includes tasks related to implementation of these capabilities and an initial pilot project focused on real-time prediction and analyses of storm surge and flooding prior to and during the landfall or during the alongshore passage of coastal storms to demonstrate Caro-COOPS's real-time interdisciplinary forecast concept. The work plan also includes a significant amount of effort in establishing linkages with other state and federal observation and data networks nationally.

This report covers progress for work performed during the period June 1, 2004 to November 30, 2004, PY03 of the grant. A Milestone Schedule is provided in Appendix A, while a summary of the status of each task is provided in Appendix B.

2.0 The Observing Subsystem

The Caro-COOPS Semi-Annual Report for PY02, submitted to NOAA on June 29, 2004, provides an in-depth overview of the evolution of the Caro-COOPS observing subsystem. This includes a discussion of the original design and the implementation strategy adopted for the Caro-COOPS observing subsystem in early 2002 prior to the outset of the project, descriptions of the components of the measurement network (instruments, platforms), and the infrastructure that was established to maintain the network, including at-sea deployment and recovery operations. It also contains an account of the initial deployment phase (2003-2004), including the challenges encountered and the consequences of these developments. A brief recounting of the sequence of events from planning through implementation provides necessary background information for understanding the rationale for the Caro-COOPS observational network, and the basis for the work accomplished to date and planned for the remainder of PY03, as well as the proposed PY04 work plan.

The Caro-COOPS observational network was conceived and designed based on: 1) what is understood of the marine meteorological and physical oceanographic processes and their effects on oceans and weather over all regional, temporal, and spatial scales in the Caro-COOPS region; 2) the infrastructure necessary to transmit data in near-real-time to the communications network and data management subsystem; and 3) available technology to measure the required oceanographic and meteorological parameters necessary for data ingestion and assimilation into hydrodynamic and hydrographic regional-to-local scale predictive models, as well as their validation. Guiding the development of the observing subsystem are fundamental principles that define its essential and distinguishing characteristics:

- Support of open, readily accessible, routine, real-time data, and products;
- Implementation based on the operational requirements for meeting users' demands, based on an 'end-to-end' concept;
- Establishment of an evolving, permanent system that is flexible, expandable and adaptable to changing information needs of user groups, changing technologies, and implementation constraints;
- Implementation in a manner that (a) facilitates full integration within the overall framework of the US IOOS and (b) enhances and supplements other federal and regional coastal and estuary observational systems in the South Atlantic Bight, as appropriate. The initial set of measurements emphasizes those state variables that are common requirements for a wide range of IOOS applications (Malone, 2001) and are among the priority variables cited by OceanUS (Ocean.US, 2002).

Monitoring and modeling are synergistic processes, and placement of the observation sites and selection of the variables to be measured are driven via a melding of known physical and biogeochemical processes and the data requirements of the Caro-COOPS modeling efforts for specific applications. In practice, the Caro-COOPS observing subsystem is being implemented in a phased and progressive manner based on sound science and technology and achievable priorities. Logistics, servicing, and monitoring tasks are daunting for a network of stations that ultimately is envisioned to span the length of the Carolinas' coast, and provide the spatial (horizontal and vertical) and temporal coverage that is necessary for a wide range of user-oriented services and products. The number and geographical distribution of the stations must be effectively balanced against very real constraints, such as the wear and tear of marine operations, weather, availability of suitable ships, and budget.

Configuration of the first phase of the observational network was driven by the requirements of the initial demonstration project on real-time prediction and analyses of storm surge and flooding before and during landfall of coastal storms. Sites and instrumentation were chosen to establish upstream, downstream, and offshore volumetric fluxes through virtual "picket fence" boundaries, as well as input and output through the air/sea interface, for model validation. Optimally, each line would include a shore-based water level station (WLS) and offshore moorings located on the inner shelf (10 m isobath), mid-shelf (30 m), and upper slope (> 75-100+ m). The lines provide inputs and outputs for the model, i.e., along-isobath flow through cross-isobath lines. The initial suite of measurements from sensors on the moored buoy systems includes vector current profiles, wave direction, wave energy spectra (from which significant wave height, dominant wave period, and average wave period are derived), water level, sea temperature and salinity at the surface and on the seafloor, and fluorescence at the surface. All parameters except wave spectra are transmitted in near real-time from the moored buoys, via the Iridium Low Earth Orbiting communication satellite system. The Caro-COOPS WLSs are identical to a NOAA National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) National Water Level Observation Network (NWLON) station. Technical specifications meet all NOAA standards, and Caro-COOPS stations are installed at historical NWLON sites. A more detailed description of the moored buoy systems, including the Iridium telemetry technology, the water level stations, and instrumentation may be found in the aforementioned Progress Report (June 29, 2004).

The initial set of seven moorings systems were deployed and three WLSs were installed during July-August 2003 along three cross-isobath "picket fences," including a line beginning in Upper Long Bay, NC, a second line above Charleston Harbor, and a third line set to the north of Hilton Head Island, SC. In the first deployment, only the Upper Long Bay line included an upper slope mooring. In addition, meteorological buoys were placed centrally within each of the boxes formed by the mooring lines to document air-sea interactions. As is to be encountered with the deployment of sophisticated sensor technologies in the harsh oceanic environment, along with pioneering telemetry and WLS systems, there have been both successes and problems associated with data collection and transmission from the initial elements of the observational network. Data transmissions from the mooring systems via the Iridium system were plagued from the outset with sporadic satellite link dropouts and missed connections that resulted in delays in receiving the most up-to-date data from the buoys. By February 2004, only the three 10-meter mooring systems were transmitting data. Significant delays in recovery operations due to breakdowns of the primary service vessel, ship collision(s) with at least one mooring system, and other technological problems contributed to damaged and lost instruments and mooring elements. There also were a variety of problems with the sensors and data transmission from the WLS soon after installation. The latter were attributed to software problems with the previously untested Sutron Xpert dataloggers and SatLink satellite transmitter.

Only five mooring systems were redeployed during March-April 2004 because of the losses from the first deployment: these were the 10-meter and 30-meter moorings on the Fripp Inlet (FRP2 and FRP3) and Capers Island (CAP2 and CAP3) lines and the 10-meter mooring on the Sunset Beach line (SUN2). However, by the end of May 2004, communications had been lost with four of the stations due to problems later determined to be related to the design and construction of the Iridium modems and antennae. Intermittent breaks in transmission continued at all WLS stations, as Caro-COOPS and NOAA CO-OPS personnel worked on technical solutions through May 2004. Thus, by the start of PY03, only the mooring at FRP2 was fully functional and regularly transmitting data.

The "post-mortem" on the initial deployments conducted at the outset of PY03 led to significant changes in the Caro-COOPS observing system. Resources committed in PY02 and proposed in PY03 to expanding the observing system were redirected to increasing its reliability. The installation of a WLS at Riseley Pier, NC was cancelled, deployment of upper slope (> 75-100+ m) moorings on all lines was indefinitely postponed, and deployment of two mooring systems off of Duck, NC, was put on hold until 2006. Instead, the focus shifted to sustaining a core array consisting of six offshore stations, i.e., moorings at the 10m and 30m isobaths of the Sunset Beach, Capers Island, and Fripp Inlet lines, and the three WLS. Funds were reprogrammed to begin to acquire backup mooring systems and instrumentation for all stations to use as replacements during scheduled maintenance or system failure and for extra ship time in the event of any emergency situations. The base for marine operations was moved to the NOAA Pier Romeo on the Cooper River adjacent to the NOAA Coastal Services Center to increase the options for employing a number of suitable ships for offshore operations.

Another major issue was the communication systems employed to transfer the data in real time from the mooring systems and WLS stations to the Caro-COOPS data center. The systems not only transfer observation data, but were also used to control the buoys' and stations' processors, dataloggers, and sensor operations, and to monitor the status of the data collection systems. Automated program notification scripts were developed to alert field operations staff to the latest conditions at each buoy, to any change in buoy location outside of a 0.05 decimal degree (approximately 300 feet) 'watch' radius, and to whether data failed to arrived during a scheduled transmission. The original Iridium modems and antennas were replaced with new models, and satellite transmission services were transferred from the Department of Defense gateway in Wahiawa, Hawaii, to a commercial gateway to insure improved support during communications failures. To meet users' requests for real-time data from the WLSs, we decided to use the data streams directly as they are received at the NESDIS receiving facility at Wallops Island, VA, rather than waiting to post the data after they have been passed through the NOAA NWLON QA/QC process. Appropriate disclaimers accompany the posted data.

In summary, the revised statement of work for PY03 included the corrective actions described above. The proposed enhancements to the observing system that remained from the original proposal included:

1) Incorporation of WEATHERPAK® weather stations on all Caro-COOPS moored buoy systems. This upgrade, recommended by our SAC, will provide the availability of weather conditions at all of the Caro-COOPS mooring sites, including wind speed and direction (gust and standard deviation are calculated), air temperature, barometric pressure, relative humidity, and solar radiation.
2) Mounting of a visibility sensor on the 10-meter buoy on the Capers Island line, seaward of the entrance to Charleston Harbor.
3) Addition of a waves processing unit to each ADCP to test the near real-time transmission of waves spectra data.
4) Installation of backup water level sensors (as required by NOAA to meet NWLON standards) and water temperature sensors to the Caro-COOPS WLSs.

Recovery of the mooring systems from the five stations was accomplished on the *R/V Savannah* and *R/V Cape Hatteras* during cruises in June-July 2004. Repairs were completed and additional mooring system components and instrumentation were received during mid-July through August.

The *R/V Savannah* was employed for the redeployment of the mooring systems on three separate cruises: FRP2 and FRP 3 on August 27-28; CAP2 and CAP3 on September 13-14; and SUN3 on October 31 – November 1, 2004. In the interval between the cruises to the Capers Island and Sunset Beach lines' stations, communication failures occurred with both of the mooring systems on the Fripp Inlet line. All communications were lost with the buoy at FRP3 soon it was deployed on August 27, and communications were lost with the subsurface instruments at FRP2 on September 20. An emergency cruise was made on the *R/V Savannah* on September 29 – October 1 to repair the FRP2 mooring and recover the FRP3 mooring. At FRP2, the buoy was brought on deck and secured for repairs without the need to haul all elements and anchors aboard. Failure was related to moisture penetrating the buoy well and causing corrosion of the SeaBird SIM card. The SIM card was replaced, and communications to sub-surface instrumentation were re-established. Future modifications to the buoy will eliminate, or at least reduce, the potential for moisture entering the well. Inspection of the mooring recovered at FRP3 revealed that the buoy failure was a result of damage inflicted by a passing ship. Abrasions on the buoy hull and elements were severe although no damage was found on the buoy tower including the GPS and Iridium antennas. However, the airlock valve was torn off during the collision, which allowed water to flood the buoy well, destroying all of the electronics, which caused the communications failure. This is twice now that we have evidence of ship damage to FRP 3, and consequently we decided not to redeploy at this site.

At the end of November 2004 (mid-way through Project Year 3), four buoys were in place and fully operational (Fig. 1). Data from the systems were directed to the Caro-COOPS data management system (Section 3.0). Values were automatically checked to ensure that they fell between previously designated instrument and regional threshold levels. Values outside these levels are flagged and maintained in the data base. During the 2nd half of PY03, we will establish a more rigorous process, based on scientific assessment to evaluate the integrity of values falling outside the threshold limits. For further information on QA/QC procedures, see Section 3.1.

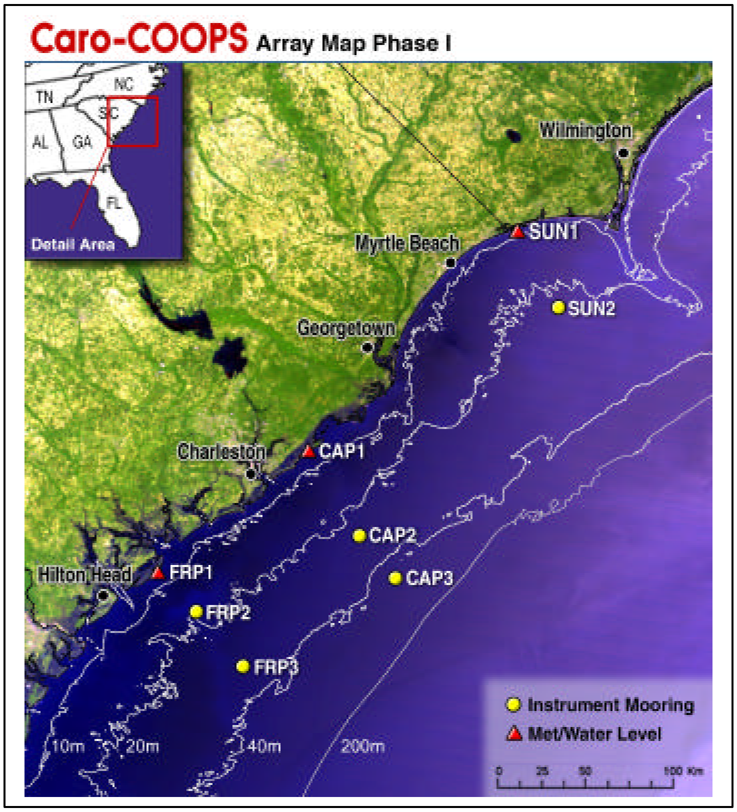


Figure 1.
The Caro-COOPS array as of March-April 2004. Frp3 has since been removed after being damaged by a vessel strike, and we do not expect to redeploy a mooring at this site.

3.0 The Data Communications and Information Management Subsystem

The Data Communications and Information Management subsystem has three primary responsibilities. First, it provides a system – automated where possible – to enable the reception, management, and transfer of observation data. Second, it insures the delivery of quality controlled data, metadata, and data products to a Web-based data and information portal that provides access to a broad user base. Finally, the data management team develops user-friendly tools and information products for observation data and model output. Within all of these development activities, our approach has been one of open access and sharing of progress (and questions) among the broader data management community, frequently through regular posting of information on community bulletin boards and Wikis on the Caro-COOPS (www.carocoops.org), SEACOOS (SouthEast Atlantic Coastal Ocean Observing System; www.seacoos.org), and SURA (Southeastern Universities Research Association; www.sura.org) web sites.

3.1. Development of QA/QC Procedures

A common imperative within the IOOS data management community is the establishment of common standards. One element of this is establishment of protocols and tools for reviewing data and providing assurance of its accuracy within previously defined limits. For example, common approaches need to be used to identify suspect data and "flag" them for those accessing the data sets. Since the development of quality assurance/quality control (QA/QC) procedures is a common issue within IOOS and government programs that operate observing systems, our QA/QC development activities are being done not only within the context of Caro-COOPS specifications, but also in association with the broader community. The development of QA/QC flags and attributes that would be included with data measurements stored to either a netCDF format or relational database fields is being analyzed and discussed by the Information

Management Working Group of SEACOOS. A collective decision on this and initial trial implementation will probably take place during the beginning months of 2005. A listing of previous developer discussion on the topic can be found at the following link http://nautilus.baruch.sc.edu/twiki_dmcc/bin/view/Main/QCNotes.

3.2. Enhancement of Data Assimilation Process

Increasingly, Caro-COOPS has been utilizing map-based products, particularly Geographic Information Systems (GIS) platforms, for visualization of data and model output. Working with GIS applications encourages a 'by variable' -- or data-type/data layer -- approach to data, with the inclusion of supporting time and location indexes for all supplied data-types. Data organized by this design better supports not only GIS functionality, but also general interoperability and data query efforts (and thus supports interoperability within IOOS). Online documentation links have been created to assist other groups with this approach (http://twiki.sura.org/bin/view/Main/DataStandards#pointForm). An example of implementation is located at http://carocoops.org/twiki_carocoops/bin/view/Main/DataloggerToPointform. We are also working with SEACOOS partners to create an additional 'flatfile' convention, which mirrors the existing netCDF functionality without the requirements of the netCDF format.

3.3. Version 2 of the Metadata Tool, Meta-Door.

An essential element of good data management and documentation, including the capability for data searching, location, and retrieval, is the development of good metadata (the information that describes the actual data values – "who, how, where, when"). Thus, we have been developing a program data and metadata management tool box, called Meta-Door, that will facilitate the development and documentation of a broad range of standards-compliant metadata and enhance access to the data behind those metadata. Meta-Door is a module-based tool box, which will have broad utility for a wide range of programs collecting observation data. The Meta-Door metadata module was released in Fall 2004, and the SensorML/MarineXML component is to be released in February 2005. Work continues towards this goal of capturing platform and sensor metadata using the Meta-Door application and making these records available as SensorML and MarineXML query or output formats for use by other community tools which will utilize these XML standards. We are also aware of the OpenGeoSpatial Consortium (OGC) 'Sensor Web' concept, which we should be able to incorporate as it develops through our use of SensorML and other OGC specifications.

3.4. Documentation

A demonstration and source code CD has been created for Meta-Door (available at http://carocoops.org/resources/MetaDoor_CD) and was distributed to SEACOOS and COTS meeting participants in Fall November 2004. These are flash presentations which give a brief overview of the system functionality as well as the java sourcecode for developers who would like to set up their own Meta-Door installation separately from the existing one publicly available (online at http://carocoops.org/metadoor) .

Technical documentation has also been made available on the Caro-COOPS bulletin board regarding some of the visualizations and graphical elements on the Caro-COOPS web site, should other developers want to create similar displays. These include:

- "How-To" technical documentation on creating dials and gauges using imagemagick, gmt (http://carocoops.org/bb/viewtopic.php?t=274);
- "How-To" technical documentation on creating query and download pages and graphs (http://carocoops.org/bb/viewtopic.php?t=330).

3.5. Development of User Tools

Access to data via the web interface has been greatly enhanced through the addition of a 'query and download' link available from the main Caro-COOPS website. When viewing any of the buoys, a 'query and download' link on the right hand side of the page allows users to plot, view, or download data for that buoy using a specified time interval or previous time range. The functionality of the plot, view, or download can also be directly invoked via http with the proper URL parameter arguments. This functionality is also available for buoy maintenance parameters such as battery, temperature, and location.

3.6. Map-Based Applications

Map-based applications, particularly Mapserver, have been explored and utilized for Caro-COOPS, SEACOOS, and OpenIOOS products. OpenIOOS is a multi-institutional/ multi-agency/private partner map-based demonstration developed to demonstrate interoperability among the various data providers; the product can be accessed at www.openioos.org. ESRI tools, which are proprietary and commonly used by many agencies and universities, have also been utilized. We also reviewed the DM Solutions 'Chameleon' tool, which allows browser 'widget' type elements, such as map distance calculators, to be defined for reuse and invoked within the MapServer browser. 'OGC Publisher' is another tool of interest developed by DM Solutions, as it is designed to enable OGC WMS(Web Mapping Service = images)/WFS(Web Feature Service = records) interaction with underlying CVS(Comma Separated Value) and relational database datasets. The group is evaluating the possibilities of rendering GIS type functionality via OGC WMS/WFS type calls, among other complex approaches.

3.0. Modeling and Applications Subsystem

3.1. Model Validation With Real Time Data

Because of the delays in being able to reliably receive real time data from the array, this activity will be scheduled for the second half of PY03.

3.2 . Model Validation with Hindcast Analysis

This activity is dealt with in Section 4.2.

3.3. High-Resolution Model Development

3.3.1. Modeling an Atlantic Low or Extra-Tropical Cyclone for array design

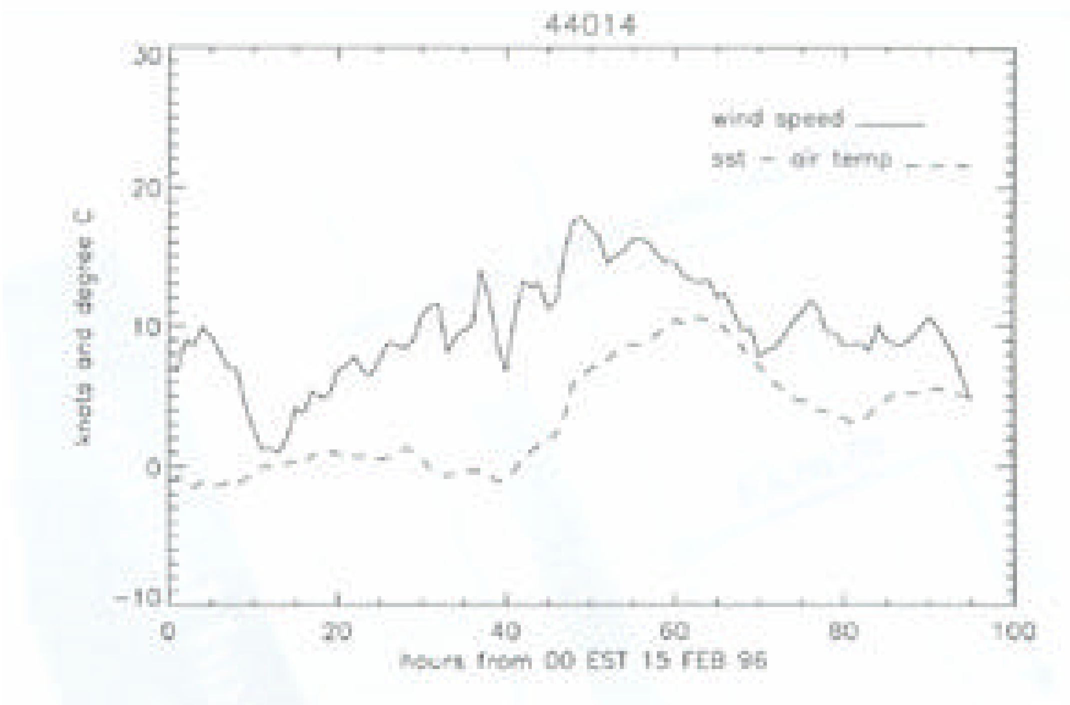
To better design the optimal backbone observing array in the Caro-COOPS domain, one of the principal justifications for a expanded suite of coastal ocean and atmospheric observations is the ability to properly sense the onset of coastal storms. From SC to VA, mid-latitude cyclones are known to become further intensified and to spawn. Storm intensification is difficult to detect in satellite imagery but could be detected with a more robust coastal monitoring network. An NRC study recommended such an expanded marine buoy network (Bosart, 1996), but questions remain on what would be measured and where. We have attempted to offer insights into the detection of a storm onset that would further our plans for the optimal coastal observing system.

We have documented the ocean atmospheric interaction during the formation and passage of a winter time atmospheric low pressure storm system which developed in the Cape Hatteras confluence of the South and Middle Atlantic Bights. These data were available from the DoE and NSF OMP Archives housed at NCSU. Utilizing an Eulerian array of oceanographic and atmospheric moorings to create the sides of a control volume, the data collected documented the fueling of the atmospheric storm and interactive coupling with the ocean. The NWS atmospheric Eta model was employed to compare theoretical to observed air-sea fluxes at measurement points in the domain and following corroboration of model results to observations, to estimate total surface fluxes. The storm was shown to have extracted energy from the ocean in the form of latent and sensible heat fluxes. While coastal lows storms per se have been well documented (Bosart et al., 1972; Bosart, 1981; Rogers and Bosart, 1986; Cione et al., 1993), actual measurements in the ocean and atmosphere during the passage of such an event have not been well documented. Based on the area of the control volume, there was an average surface heat flux loss of $596 W/m^2$ during the event. However, over the period of storm initiation and passage, there was a net gain of heat through the sides of the control volume -- a truly remarkable finding. The storm was infused with energy from below as it passed over the C-C domain. Cione et al (1993) and Li (1995) determined the average paths of winter-time atmospheric lows through the region. The ETC studied herein moved along that path. This study suggests that more air-sea flux data along the mean path is needed as one can clearly detect the onset of the event in the change of air-sea temperatures across the navi-face (Fig. 2a, b). Data from the array would give warning of the onset and would be assimilated into coupled atmospheric-ocean models. The proposed optimal observation network is based partially on these findings.

The study demonstrated that air-sea flux observations and calculations can be used to detect the intensification and or formation of an ETC. These data will not only be of use in NCEP models but will alert WFO forecasters that a storm is being intensified or spawned. What is documented is the need for on-site data in the region of principal Atlantic Low cyclogenesis and further intensification. Without additional data, storm onset cannot be forecast because the pre-conditioning cannot be recognized and forcasts of storm tracks as well as type and quantity of precipitation are compromised. NCEP is doing what it can but needs more data from these data starved regions, especially the epi-center of cyclogenesis on the US eastern seaboard. This finding should be shared with NOAA NCEP via NOS as rationale to make a case for a more robust coastal buoy observing network, particularly in the alongshore swath extending from south of Charleston to the Delmarva Peninsula, with a centroid offshore of Cape Hatteras. Without this expanded network, Atlantic Low storm models cannot be properly initialized and forecasts of ETC intensities and tracks will continue to be limited and lacking. Moreover the C-C observing array becomes a multi-use use system. The data can also be used to initialize the Caro-COOPS hydrodynamic model, which will allow for winter storm forecasts of coastal currents and waves, coastal flooding and inundation and for the assimilation of the data directly into the models -- both ocean and atmospheric.

3.3.2. Modeling Hurricane Wind Fields

An asymmetric hurricane model based on the well conceived Holland hurricane model (1980) has been developed by: 1) incorporating an asymmetric term into the Holland model; 2) using NHC hurricane guidance for prognostic prediction; 3) assimilating NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) Hurricane Research Division (HRD) surface wind analysis into the model: and 4) assimilating National Data Buoy Center (NDBC) real time buoy wind data into the model. The method has been validated with four recent hurricanes, namely Floyd (1999), Gordon (2000), Lily (2002), and Isabel (2003). These four hurricanes were chosen because of the availability of significant levels of archived NHC forecast guidance. For each hurricane, a series of 6 hour and 12 hour hurricane wind forecasts were conducted using the NHC guidance and buoy data available at the initial time when the forecasts were made. Thus, the wind fields produced by the model are true forecasts. The results using the new asymmetric hurricane wind model developed in this study were compared against the results using the traditional Holland model, buoy observations, and the HRD hurricane surface wind analysis. The comparisons showed that the asymmetric model improves the forecasts performance in all four hurricane cases. This means that the C-C hurricane wind-field is now the state of the science wind-field to our knowledge.



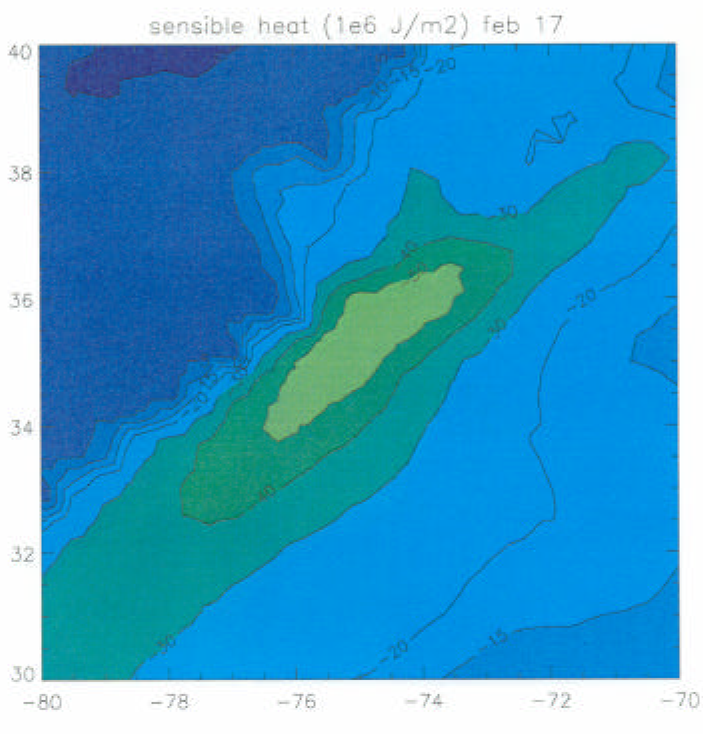


Figure 2.

a) Air-Sea temperatures and winds collected at NDBC buoy during the onset of an ETC in the C-C domain;

b) The sensible heat flux swath through the C-C domain

3.3.3. Wave Field Modeling

One of the critical challenges in the Caro-COOPS program is in providing wave field information in near real time, as well as model forecasts. We have focused on four separate efforts in this regard: (1) conducting wave field modeling during the passages of hurricanes; (2) making wave forecasts in the presence of varying waves over variable topography; (3) making wave forecasts in the region of the Gulf Stream Front and beyond; and (4) providing wave information as both "now-casts" and "fore-casts". Each is a separate challenge, but progress is being made for each.

3.3.3.1. The Wave Field During Hurricane Passage

Depth-induced wave breaking plays an important role in the actual manifestation and the modeling of the wave field in shallow water areas. The resolution of bottom topography and model resolution impact the modeled structure of the wave field as well. To date, five hurricane cases have been used to investigate shallow water and topography variability impacts on the wave field. The Holland (1980) hurricane model was used to simulate the wind field in our model experiments, along with the model pair of the NAVY SWAN model with wave breaking included and NOAA's WAVEWATCH-III, for each of the five hurricane cases. The results were then compared to NOAA NDBC buoy data. Additionally, two nesting approaches, one with SWAN nested within itself and then with SWAN nested into WAVEWATCH-III, was tested for each case. Model results show that wave breaking is not always required for the proper modeling of the wave field in hurricane cases, even in coastal areas. Wave breaking has more of an impact on the Significant Wave Height (SWH) of waves in coastal areas the zones which lie to the right of the hurricane track than they are in zones which are located to the left of the hurricane track. The results of the nesting experiments show that there is no significant deviation between the different nesting cases and the SWAN case.

3.3.3.2. Wave Interactions With Currents

Actual observations of the wave field using bottom mounted ADCPs are actually measuring the wave field as it is, i.e. as an outcome of its interactions with the current field. Thus, to properly model the wave field, for prognostic purposes, we must analyze the effect of currents on waves and the effect of waves on currents and the interactive coupling between them as has been previously shown (Xie, Pietrafesa and Wu, 1998). The wave climate -- past, present and future -- is useful information for coastal stakeholders. To address this issue the SWAN, Wave Watch III wave models and the HYCOM hydrodynamic models have been employed. Several interactions have been considered to date.

3.3.3.2. Wave Interactions With the Gulf Stream

When waves encounter the Gulf Stream, there can be subsequent penetration, absorption, reflection, or refraction. Moreover, winds are always present. We have investigated the suite of possibilities and have made significant progress. For example, preliminary findings indicate that currents will reduce (increase) significant wave height when waves propagate following (opposing) the current direction. With southwesterly winds present, when waves enter the Gulf stream, the mean wave direction is found to rotate clockwise, and bend off from the Gulf Stream normal. This phenomenon is caused by wave refraction due to the Gulf Stream and can be predicted by the refraction equation. Other cases are being studied.

3.3.3.3. Providing Now-casts and Forecasts

We have used NDBC buoy (41004) data and Scanning Radar Altimeter data (SRA) during the passage of Bonnie 1998 to evaluate the model results using the Gulf Stream simulated by the HYCOM current model (Fig. 3, 4). In the future, we expect to be able to forecast the wave fields and the current fields using a Caro-COOPS region wave-current coupled model.

3.3.3.4. Forecasting Waves From Data

We have created relationships between winds and waves that will allow for us to use the actual real time data stream coming in from both the Caro-COOPS and the NOAA NDBC buoys to forecast winds and waves at the buoy site in hourly intervals out to 12 hours. We have established confidence intervals around the forecasted winds and waves and expect to roll this product out in March 2005. This product should be very useful and derives from a statistical model.

3.4. Modeling the Gulf Stream

Fishermen and weather forecasters, amongst many, have a daily need to know the location of the Gulf Stream and its west wall front off the Carolinas. Satellite imagery is often a useful tool to help in that regard, but it cannot always demonstrate where the Gulf Stream is located, particularly its west wall front, due to the excessive cloud cover through most of the year in the coastal Carolinas. Here a model may be the best backup solution and we report on a Gulf Stream modeling effort.

The role of the Gulf Stream (GS) off the Carolinas is multi-fold; (1) the GS is a source of nutrients; (2) it plays a role in absorbing, reflecting or refracting offshore wave energy; (3) it is a key component of the further intensification and or spawning of winter storms, a variety of which are categorized as Atlantic Lows, Extra-Tropical Cyclones or Hatteras Lows; (4) it has been known as the beltline on which toxic algal blooms which originate on the West Florida shelf can be brought to the Carolinas coast; (5) the GS deflection at the site of the Charleston Bump and subsequent creation of the Charleston Trough are important fishing grounds for the SC fishing community, and information concerning the location of the GS Front can be important, economically and temporally; and (6) the GS can play a role in the further intensification of Tropical Cyclones as demonstrated by Bright, Xie and Pietrafesa (1999).

As both an interoperability modeling exercise and to begin creation of an operational Gulf Stream per se forecast model, we are focusing on a well documented Red Tide event that occurred on the coasts of the Carolinas in 1987. Pietrafesa et. al. (1988) showed that a combination of atmospheric winds and the Loop Current-Florida Current-Gulf Stream system transported toxic dinoflagellate cells from the west coast of Florida to the NC coast. The winds advected the toxins from NC to SC waters. Pietrafesa et al. (1988) showed that off the Carolinas, warm Gulf Stream frontal filament waters associated with meanders of the Gulf Stream (Pietrafesa and Janowitz, 1980) can be disrupted by strong, persistent northerly winds and subsequently transported the toxic dinoflagellate cells from the Gulf Stream front to near-shore area across the continental shelf causing a Red Tide bloom. Therefore, the mechanism of the generation and evolution of Gulf Stream frontal waves, i.e. meanders and eddies, is very important in the understanding and simulation of Red Tide blooms off the NC and SC coasts. The region to region telecommunications (Gulf of Mexico to South Atlantic Bight) can best rely on the real time reporting of data from the separate regional systems.

Moreover onshore movements of offshore waters have been shown to relate to bottom bathymetry geometry (Janowitz and Pietrafesa, 1983; Pietrafesa, 1986). Following Janowitz and Pietrafesa (1983) we find that there are three factors which constitute the variations in bathymetry in the SAB are principally: curvature of the isobaths; divergence and convergence of isobaths; and the Charleston Bump. To test the combined effect of the three factors, a set of numerical experiments was designed. To more properly simulate GS movements the HYCOM has been used to do numerical simulations with different bathymetries. A nested approach is used to increase the horizontal resolution. The outer domain includes the north and equatorial Atlantic Ocean with horizontal resolution of 0.18 degree, while the inner domain includes the C-C region with horizontal resolution of 0.06 degree. The ocean model is spun up for one year with atmospheric forcing from COADS in the 0.18-simulations, and the inner-domain simulation is run from the second year. All analyses are based on the 0.06-simulations. Simulations are proceeding. Preliminary results show that both the convergence/divergence of the isobaths and the bump on the sea floor can generate Gulf Stream meanders and eddies. .

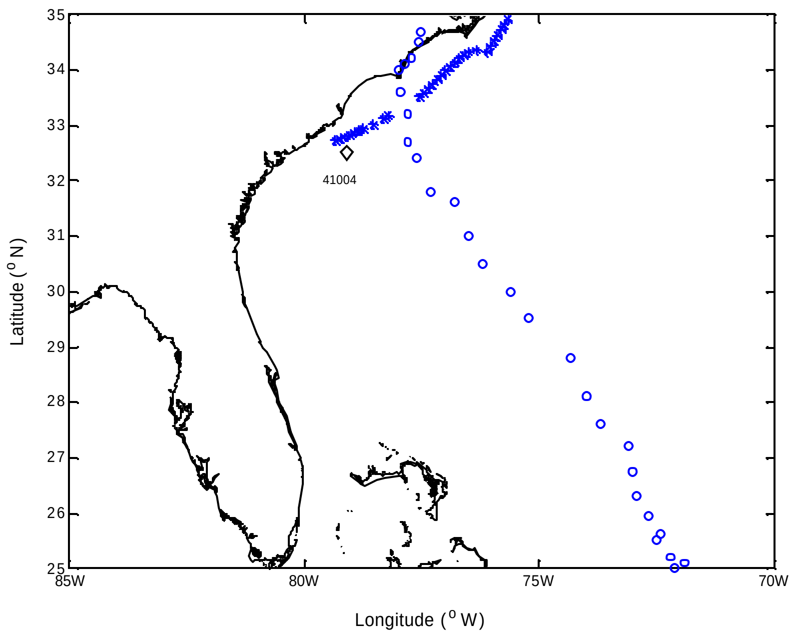


Figure 3. Observation points of SRA directional wave spectra at landfall on Aug. 26 1998 of Hurricane Bonnie. Circle point represents the track of Bonnie.

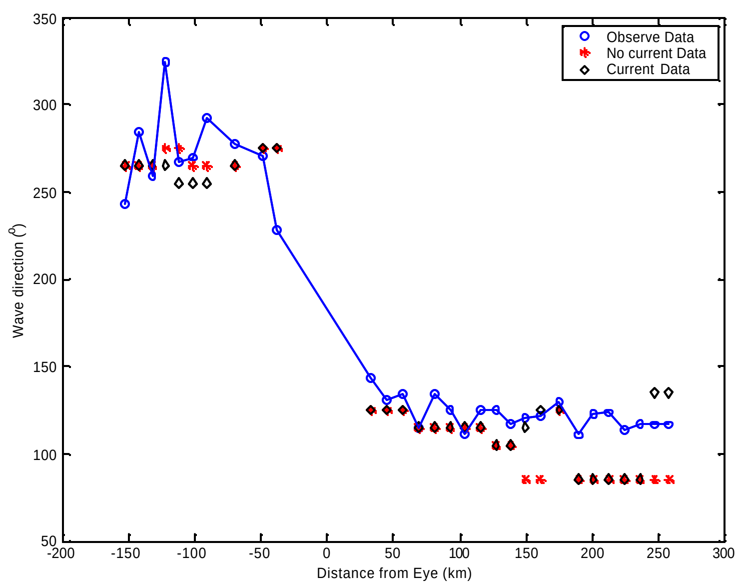


Figure 4.
Comparison of SRA observation and model simulation for peak wave direction along the section across Hurricane Bonnie shown in Figure 3.

4.0. Demonstration Project: Coastal and Inland Flooding Prediction

Hurricane induced storm surge and inundation have been studied extensively across the large spatial extent of the Caro-COOPS domain. The study has considered further development of the existing model system, validation of the model system using historical events, a planned and well coordinated hurricane-induced surge and flooding drill with the SC-EMD using a past hurricane as a virtual surrogate, as well as several real time forecast drills during the past hurricane season and improvements to the model architecture. The model system performed very well, particularly along the coast, for the simulated case of Hurricane Hugo 1989 and all hurricanes that struck the area in the 2004 season. The simulated maximum storm surge and the overall inundation scale agree quite well with observations. Yet there are several issues to be more properly addressed and discussed below.

4.1. Model configuration of Charleston Harbor

Charleston Harbor is important for the study of hurricane impacts across the Caro-COOPS domain because of the vulnerability of its dense population, heavy shipping activities and solid documentation of surge and inundation accompanying Hurricane Hugo, 1989.

The topography in Charleston Harbor and its adjacent coastal area is sufficiently complicated that an encapsulating technique is required to nest the high horizontal resolution inner zone, reflecting the complex topography, within a relatively lower resolution outer zone, itself nested within a larger domain; like Russian Marushka dolls. Nested models fall into two categories, passive and interactive or 1-way and 2-way, respectively. 1-way nested models use boundary conditions along the periphery of the high resolution region obtained from outer domain lower resolution calculations, and so on. 2-way models, in addition to providing boundary conditions for the fine grid region, allow the evolution within the fine grid to influence the evolution of the coarse grid as well. As the spatial scales of hurricanes are far larger than those of focused areas such as Charleston Harbor, and the propagation of storm induced energy generally follows the shoreward motion of the storm, from the outer to middle to inner domains, the 1-way nesting approach is deemed adequate; particularly in an operational mode.

Three domains are nested for Charleston Harbor hurricane studies (Figure 5). The outermost domain is 1 minute, the mid domain 12 seconds, and the innermost domain 3 seconds as the horizontal spatial grid sizes. Four sigma levels are used in the vertical throughout. Bottom topography was obtained from the GEODAS, version 4.0.7, and a minimum depth of 1m was given where the mean water depth is less than 1m.

4.2. Model Validation for Charleston Harbor

Model validation was effected via a comparison of model simulation results with observed data during passages of selected hurricanes such as Hugo 1989, Isabel, 2003, and all those in 2004. For flood validations, the simulated maximum inundation results agree very well with the documented flood lines in all regions except for areas where the offshore wind direction favored the evacuation of water, such as, as Hugo was about to make landfall. This finding posed the question of whether or not the model inundation scheme, initially developed for a semi-enclosed coastal lagoon, the Pamlico-Albemarle Sound system, could work well in an open system like Charleston Harbor. So a new scheme was developed that assumes that $C_t\ (gh)^{1/2}$ is the flood inundation speed, where C_t is a terrain related parameter, g is the acceleration of gravity and h is the depth. This new assumption may apply to open coastal systems; harbors, coastal plane estuaries, etc.

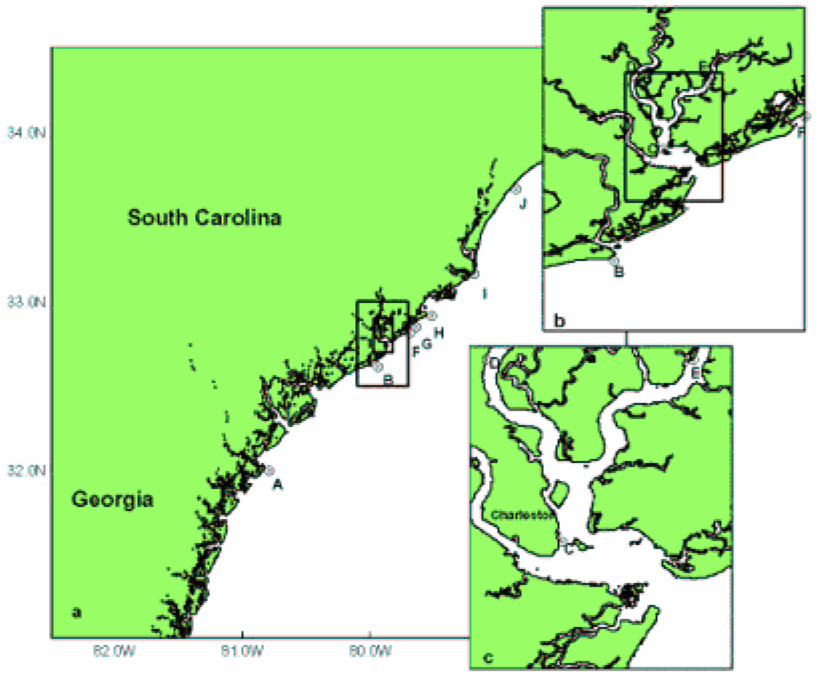


Figure 5. Triple nesting for Charleston region.

4.3. Hurricane induced storm surge and inundation in Charleston Harbor

Hurricane Hugo's track is only one of the possible paths that a hurricane may take. Figure 6 illustrates 12 possible tracks which are either parallel, perpendicular to the coastline or which make landfall in the center of the harbor. Inundation products have subsequently been produced to provide further guidance to SC-EMD and local NWS WFOs, which is an advance over the existing MEOW product currently employed.

The simulation results indicate that, for hurricanes whose paths run parallel to the coast, severe storm surge and inundation along the coast and harbor are produced by those hurricanes that are within the range of Radius of Maximum Wind (RMW) from the coast. As the track gets closer to the coast, the storm surge gets higher and the inundation extends farther inland. For the four hurricanes with tracks perpendicular to the coast, Track 7 is the one that produces the most severe storm surge while Track 6 induces the most severe inundation. The maximal cases for both surge and inundation for all perpendicular hurricanes (not limited to the four assumed ones) could be along a swath somewhere between Tracks 6 and 7. Thus, the track producing the greatest surge and the track producing the largest extent of inundation are not the same. This is a very important result. Surge and inundation are not the same and one must be careful to qualify predictions accordingly. Curiously, if the hurricane's parallel track is located to the northeast side of the mouth of the harbor (Track 8), storm surge and inundation are no longer a threat to the harbor. When the track distance is only 30km away from Charleston, there is no inundation across the entirety of the Charleston Harbor region. The surge is relatively negligible as well. In this case, the maximum sea surface elevation remains negative for most regions in the vicinity of the harbor. For hurricanes that make landfall at Charleston, the most severe inundation is produced by the track that comes from a direction between south and southwest. The highest storm surge is produced by the track that parallels (or nearly parallels) the coast. As the track turns towards the coast, the extent of both surge and inundation is dramatically reduced.

4.4. A Real-time Forecast Test

The ability to respond relatively quickly to SC-EMD and local WFOs is the key to a successful real-time flood forecast for Charleston, now that the model system has been successfully developed and validated. While the interactions between the harbor, the rivers and their watersheds are still being developed, the advances made are significant. The reason that quick response is necessary is because the NWS NHC forecast for an approaching hurricane's track, intensity and translation speed forecast changes over time. Thus, the subsequent storm surge and inundation model has to have its wind force input, i.e. the wind model, updated whenever the new weather forecast is available. We have developed an anti-symmetric hurricane wind field model based on the well established symmetric Holland (1980) TC model that shows great promise for providing more accurate input for the surge and inundation model -- a significant advance.

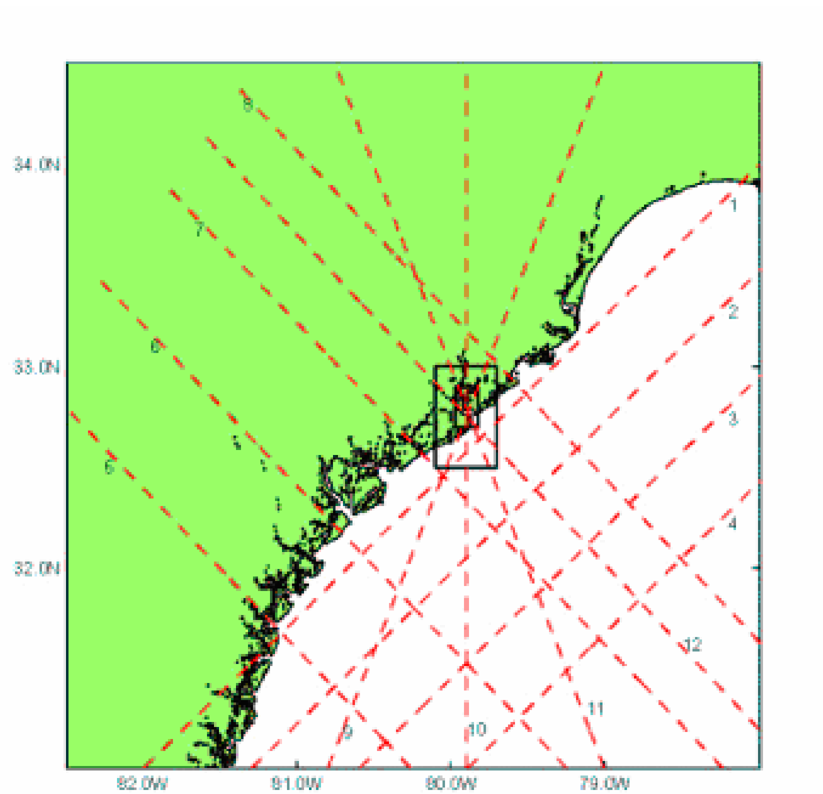


Figure 6. Variety of paths assumed for hurricane surge and flood inundation from which next generation individual MEOW maps have been and are being created for SC-EMD and NWS WFO guidance. Maps are dependent on hurricane category, translational speed and wind field asymmetry also. Maps will be accessible through an interactive interface on the Caro-COOPS website.

Our prognostic experience during the 2004 hurricane season strongly suggests that storm surge and inundation must be forecast in different stages, based on the track, intensity, and speed and distance of a hurricane from the coast. When the approaching hurricane is 3-5 days from landfall, an inundation probability forecast is a reasonable and reliable forecast. At this stage the hurricane track cannot be precisely determined by the NWS, and we must resort to a sector of possible tracks, with other weather information, such as central pressure and maximum wind speed, used to drive the storm surge and inundation model. For example, almost a week before Hurricane Charley (2004) made landfall over Ocean Isle Beach, NC (LJP personal experience), the NWS made its most probable track forecast, and we produced the inundation probably forecast shown in Figure 7. As the hurricane approached the coast about 1-2 days prior to landfall, an updated storm surge and inundation forecast was made based on the official government track forecast. Also for the case of Hurricane Charley, the Caro-COOPS real-time storm surge and inundation forecasts were made using the #18 NWS forecast report for Charley, before landfall. In addition to Hurricane Charley, Caro-COOPS storm surge and inundation forecasts were made for Alex, Bonnie, Frances and Jeanne over 2004. It was a particularly active season for the southeastern region.

Figure 7.

Percent probability inundation map provided to SC-EMD in two days in advance of Hurricane Charley as discussed above.

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4.5. A Resolution Sensitivity Experiment

The study domain for the horizontal resolution sensitivity experiment is the triple nesting system shown in Figure 5. Hurricane Hugo was used to drive the storm surge and inundation model. The horizontal grid size of the original innermost domain is 80m.. The bathymetry data quality (rounded to the 10^{th} meter) is higher than its counterpart of land relief (rounded to integer meters). To evaluate how much difference is induced by higher horizontal resolution bathymetry/land relief data used in the model system, the recent 50m Charleston Harbor topography file was invoked for the resolution sensitivity study. The precision of bathymetry and land relief (particularly the latter) is greatly improved in this higher resolution data file. The resolution improvement increases grid point numbers in the innermost domain from 317x357to 542x576. Results indicate that storm surge is not appreciably different when the two different topographic data sets are used in the model. The inundation scale is, however, decreased when the higher resolution data are employed. Two factors may induce such a difference. One is the resolution increase itself. The other is the improvement of land relief data due to resolution improvement. To identify the responsible factor, the lower resolution data (80m) were interpolated to a file with the same resolution of the higher (50m). In a separate exercise, the higher resolution data were degraded. All results and comparisons suggest that it is the land relief data quality, not the horizontal resolution that makes the difference. This finding will help in future inundation modeling efforts. Scrutiny of the two different topography data sets reveal that land relief value is not appreciably different when the location is farther inland, ~ a couple of kilometers from the coastline. It is, however, very different along the coast. The 50m data file accurately reflects coastal man-made structures such as dams and jetties while the 80m file does not. This is a significant difference.

4.6. The Sea Level Retreat Problem

The storm surge and inundation model that has been configured for the Caro-COOPS domain behaves very well and shows great performance for its simulation of the overall maximum storm surge and the inundation. However, following landfall, and when sea level along the coast in the hurricane's south-west quadrant begins to fall, the model loses performance. The consequences are the likelihood of improperly predicted land return routes provided to EMDs. This was found to be true in the Caro-COOPS forecast for Hurricane Isabel, Hugo (1989), Emily (1993), Alex (2004), and Charley (2004). We are working to find the source of the problem, generic to all surge and flood models.

4.7. The Period Remaining in PY03

An immediate and necessary step is to find the mechanism leading to the incorrect water retreat model prediction. There are two possible error sources: (1) wind-model inadequacy and (2) incorrect behavior of the storm surge and inundation model under extreme wind force. At present, the Holland Wind Model, HWM, (1980) is coupled with our storm surge and inundation model. The HWM is axis-symmetric or circular. However, real hurricane wind fields are different in at least two aspects. One, for a real hurricane, the wind force in the right-forward quadrant, in most cases, is stronger than in the upper left-hind quadrant. The other aspect is the inflow angle. The wind force difference in different quadrants has been considered, as a Holland Wind Field modification, in our storm surge and inundation model. But the inflow angle effect has not been reflected in our model code. Hence, the inflow angle correction continues to be a focus of study. .

Another focus is the completion of the development of two additional high density regions in the C-C domain. Two or three nested domains will be set up for Myrtle Beach and Beaufort/Hilton Head. Pre-event model runs of hurricanes with different tracks, intensities and RMWs will be executed in all sub-domains of each nesting system. As a result, a bank of storm surge and inundation digital results in these locales will be built, offering valuable evacuation information to the SC-EMD.

4.8. Implications

The CEMEPS surge and inundation model, though not yet complete, is the state of the science for coastal surge and inundation operational models. We hope that this model will be introduced to NOAA's National Center for Environmental Prediction (NCEP) via the NOAA NOS Charleston Coastal Services Center for adoption consideration.

4.9. Interactions With Stakeholders

Model outputs were used to develop a demonstration version of an interactive flooding risk assessment system (StormMap), which was presented to emergency management officials in Charleston County, SC in July 2003 to gain preliminary feedback regarding the system's design and potential value. In April-June 2004, several meetings were held with the South Carolina Emergency Management Division (SC EMD) to discuss the potential contributions of Caro-COOPS hurricane storm surge forecasts, and the utility of alternative information displays, formats, and delivery methods.

During this summer's active hurricane season, we were able to test our product's design, delivery, and internal workflow during the approaches of Hurricanes Charley, Frances, Gaston, and Jeanne. In the event of an approaching hurricane, the Coastal Atmosphere and Ocean Modeling group at North Carolina State University generated storm surge forecasts based on updated hurricane track forecasts issued by the National Hurricane Center. The data management group based at the Baruch Institute for Marine and Coastal Sciences at the University of South Carolina transformed these forecasts into useful information products, which included 1) storm surge "probability of inundation" maps, 2) and static and animated GIS shape file layers of flooding and drying depths associated with storm surge. These were posted to a restricted web site and accessed by the SC EMD for their information and use during approach of the storm. Feedback from the SC EMD was positive, and we identified several possible improvements to incorporate before the next hurricane season.

Key areas for improvement include expanded coordination and collaboration with other public (e.g. National Hurricane Center, Coastal Services Center) and private interests (e.g. real estate, insurance, utilities), as well as with other storm surge planning, modeling, and response efforts and information products in the southeast region. The Caro-COOPS StormMap GIS product can be further improved and linked with pre-generated model simulations to support hurricane planning efforts, earlier surge forecasts for approaching storms, and the presentation of alternative scenarios.

5.0. Demonstration Project: Living Marine Resources Management

5.1. Formation of Stakeholders Group

This is scheduled for the second half of this project year.

5.2. Development of the Project Plan.

A number of steps have been taken to initiate the planning process. In October 2003, Caro-COOPS hosted a fisheries stakeholder workshop in Charleston, SC to learn more about the information needs of fishers, managers, and academics. Commercial and recreational fishers described data needs concerning 1) the general safety of marine operations (see "Mariners" section below), and 2) the identification of prime fishing locations. On the resource management side, we have begun consultations with the South Atlantic Fishery Management Council (SAFMC) and South Carolina Department of Natural Resources (SCDNR) to assess data needs and opportunities for cooperation towards the linking of ocean observations with fisheries-related data collections.

In September 2004, Caro-COOPS investigators attended a SAFMC workshop concerning the development of a web-based, GIS-enabled information system that will integrate data collections related to benthic habitats in the southeast region and support the SAFMC's mission of managing fisheries on an ecosystem basis. Caro-COOPS has also begun to have discussions with the SCDNR concerning their development of a web-based GIS to support fisheries management by integrating three decades of fish survey data with marine protected area boundaries and coastal ocean observations. Caro-COOPS continues to collaborate closely with the Southeast Atlantic Coastal Ocean Observing System (SEACOOS) in meeting the needs of fisheries managers in the southeast, as Caro-COOPS is now formally recognized as an affiliate of SEACOOS.

Appendix A: Caro-COOPS Timeline as Presented in Proposal.

TASKS	J04	J04	A04	S04	O04	N04	D04	J05	F05	M05	A05	M05
The Observing Subsystem												
Semi-annual array turnaround		■	■					■	■			
Deploy moorings off Duck, NC	■											
Upgrade moorings for meteorological measurements	■	■	■									
Deploy experimental nearshore waves measurement system									■			
Install water level measurement systems						■						
Real time oceanographic & meteorological data	■	■	■	■	■	■	■	■	■	■	■	■
Data QA/QC	■	■	■	■	■	■	■	■	■	■	■	■
Annual maintenance of coastal WLS										■	■	
Data Communications and Management Subsystem												
Develop QA/QC procedures	■	■										
Enhance data assimilation process	■	■	■									
Version 2 of metadata tool	■	■	■									
Documentation				■	■	■	■	■	■	■	■	■
Development of user tools	■	■	■	■	■	■	■	■	■	■	■	■
Modeling and Applications Subsystem												
Model validation with real time data	■	■	■	■	■	■	■	■	■	■	■	■
Model validation with hindcast analyses	■	■	■	■	■	■	■					
High-resolution model development						■	■	■	■	■	■	■
Demonstration Project: Coastal and Inland Flooding Prediction												
Validate Storm Surge & Flooding Model Charleston Harbor	■	■	■	■								
Beaufort County simulation	■	■	■	■	■	■	■	■				
Myrtle Beach simulation					■	■	■	■	■	■	■	■
Form stakeholders group	■											
Product development and delivery				■	■	■	■	■	■	■	■	■
Demonstration Project: Living Marine Resources Management												
Form stakeholders group	■											
Develop project plan		■	■	■	■	■	■	■	■	■	■	■

Appendix B: Summary of Task Status

The Observing Subsystem

- Semi-annual array turnaround: Ongoing.
- Deploy moorings off Duck, NC: Deferred until PY04.
- Upgrade moorings for met measurements: Completed for Sun2; rest scheduled for summer turnaround.
- Deploy experimental nearshore waves measurement system: Deferred indefinitely.
- Install water level measurement systems: Completed.
- Real time oceanographic and meterological data: Completed for oceanographic data and Sunm2 met data.
- Data QA/QC: Ongoing.
- Annual maintenance of coastal WLS: Ongoing.

Data Communications and Management Subsystem

- Develop QA/QC procedures: Ongoing.
- Enhance data assimilation process: Steps completed, but ongoing.
- Version 2 of metadata tool: Completed.
- Documentation: Number of web documents completed; ongoing.
- Development of user tools: Map-based products and web site produced; ongoing.

Modeling and Applications Subsystem:

- Model validation with real time data: Scheduled for second half of PY03.
- Model validation with hindcast analyses: Completed for Hugo; ongoing.
- High-resolution model development: Steps completed; ongoing.

Demonstration Project: Coastal and Inland Flooding Prediction

- Validate storm surge/flooding model for Charleston Harbor: Completed.
- Beaufort County simulation: In production.
- Myrtle Beach simulation: In production.
- Form stakeholders group: Group identified; first meeting will be in second half of PY03.
- Product development and delivery: Products produced for SC EMD in 2004; ongoing.

Demonstration Project: Living Marine Resources Management

- Form stakeholders group: Scheduled for second half of PY03.
- Develop project plan: In process.